Color Matching for High-Quality Panoramic Images on Mobile Phones

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**Abstract — ***We present an efficient image stitching approach for creating high-quality continuous circular 360-degree panoramic images. We address the problem of color and luminance correction for long, 360-degree image sequences, where the source images have very different colors and luminance. Color matching is used for minimizing both the color differences of neighboring images and the overall color correction over the whole sequence. We perform gamma correction for the luminance component and linear correction for the chrominance components of the source images. The color consistency problem of 360-degree panoramic images is addressed by color correspondence and color difference distribution processes. We implement the stitching approach in a panoramic imaging system for creating high-resolution and high-quality panoramic images on mobile phones[1].*

Index Terms — Mobile panorama, color correction, color blending, image labeling, image blending, color matching, color consistency, continuous circular 360-degree panorama.

I. INTRODUCTION

A. Panoramic Images on Mobile Phones

Modern mobile phones have become computational devices equipped with high-resolution cameras, high-quality color displays, and powerful 3D graphics processors, which makes it possible to develop applications for mobile computational photography and augmented reality. Mobile panoramic imaging [1], [2] allows the user to create panoramic images on mobile phones and share them right away.

However, compared to desktop computers, mobile phones still have some disadvantages, including limited amount of memory and computational power. In this paper, we address the color processing problem and develop an efficient 360-degree panorama stitching approach suitable for running on a camera phone.

B. Related Work

Our work is mainly related to image stitching including color correction, image labeling, and image blending.

Color correction is used for reducing color differences between source images and balancing colors and luminance in the whole image sequence. Approaches based on linear models [3]-[6] (either in linear *RGB* or gamma-corrected *sRGB*) are simple and fast, however, accuracy of color correction is not high. Color saturation during the color correction process is one of the main problems in such approaches. With more intensive processing, and assuming pixel-accurate registration of the images, even higher quality can be achieved [7], [8].

Image labeling is used for finding optimal seams where the differences between source images are minimal and then merging them together along the seams. The optimal seams can be found by graph-cut, dynamic programming, or other approaches. The graph-cut based approaches [9], [10] can find global optimal seams with random image order, however, computational costs and memory consumption are high. On the other hand, the dynamic-programming-based approaches [11]-[13] can find optimal seams very fast with low memory consumption.

Image blending is used for reducing color differences between source images and smoothing color transitions for the whole panoramic image. Gradient domain image blending [14], [10] can provide high-quality blended images. However, computational costs and memory consumption are high. Recently, Farbman et al. [15] created instant image cloning that uses mean value coordinates to distribute color differences on the seam over all pixels of the image to be blended. The approach is simple and effective. It speeds up the blending process and reduces memory consumption.

C. Our Work

Based on our previous work on a mobile panoramic imaging system [1], [2], we develop an efficient image stitching approach for creating high-quality continuous circular 360-degree panoramic images on mobile phones.

We address the problem of color differences of source images in the image sequence by matching the differently exposed images. Depending on image content, different images are exposed and white-balanced differently, leading to differences in both the luminance and chrominance for the same objects seen in two overlapping neighboring images. We perform a new gamma-correction that matches the luminance content of neighboring images within the area of overlap, and a linear correction for the chrominance components. This approach avoids the overflows of most linear methods, yet provides high-quality output. In order to make the approach more robust to the quality of spatial alignment, we match corrected means of luminance and colors in the overlapping areas of source images. This approach also reduces computation requirements, making the approach suitable for running on mobile phones.

The basic color matching approach was recently published at a conference [2]. Here we extend and apply it to circular 360-degree panoramas. Additional color constancy constraints

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exist between the beginning and ending areas of a 360-degree panoramic image. During the color correspondence process, we add information of these two areas into a global color matching process to obtain color correction coefficients to balance colors and luminance in the whole image sequence. The differences between all areas of a continuous circular 360-degree panorama are reduced, including the transition from the end back to the begin. In the color difference distribution process, we find an optimal seam between the begin and end areas, merge them together along the seam, and blend the color differences to enforce color consistency for a circular 360-degree panoramic image.

We have implemented the panorama stitching approach in a panoramic imaging system running on mobile phones for creating high-quality panoramic images. We demonstrate the approach with various image sequences and obtain good results and performance.

II. Work Flow of the Stitching Approach

Fig. 1 shows the workflow of our panorama stitching approach with color matching. It creates a sequential procedure to stitch source images to a panoramic image one by one. As we can stream the output image to a file, we never need to keep the whole large output panorama in memory at full resolution, which is important for saving memory.

We start by setting the stitching order for source images in the image sequence. Next, we calculate color correction coefficients by color matching. For each source image, we compute mean values for chrominance components and the logarithmic mean value for the luminance component in the overlapping area of adjacent images. An error function in color correction coefficients can be created by color matching with the mean values for each color channel. After minimizing the error functions with a global optimization process, we obtain the color correction coefficients for each source image.

Then, we perform image stitching to create a panoramic image with a sequential procedure. For the current source image, we perform gamma correction to match luminance and linear correction to match chrominance. If the current image is the first image, we put it to the current panoramic image directly by encoding and saving it into the panoramic image file. Otherwise, we find an optimal seam between the previous image S_{i-1} and the current source images S_i with dynamic programming and merge them together along the seam. In order to reduce color differences between these two images and smooth color transitions in the panoramic image, we perform image blending with an error diffusion process. We compute color differences on the seam and spread the color differences over all pixels in S_i on the S_i side of the seam. We update color and luminance values of these pixels by adding the contributions and put them into the current panoramic image by encoding and saving them into the panoramic image file. In this way, we can smooth color transitions of the current panoramic image. We repeat this processing for all source images. At last, we find an optimal seam between the first and last areas of the panoramic image, merge them together to create a continuous circular 360-degree panoramic image, and enforce color consistency with the color difference distribution process. We put the merged composite into the current panoramic image by encoding and saving it to the panoramic image file.

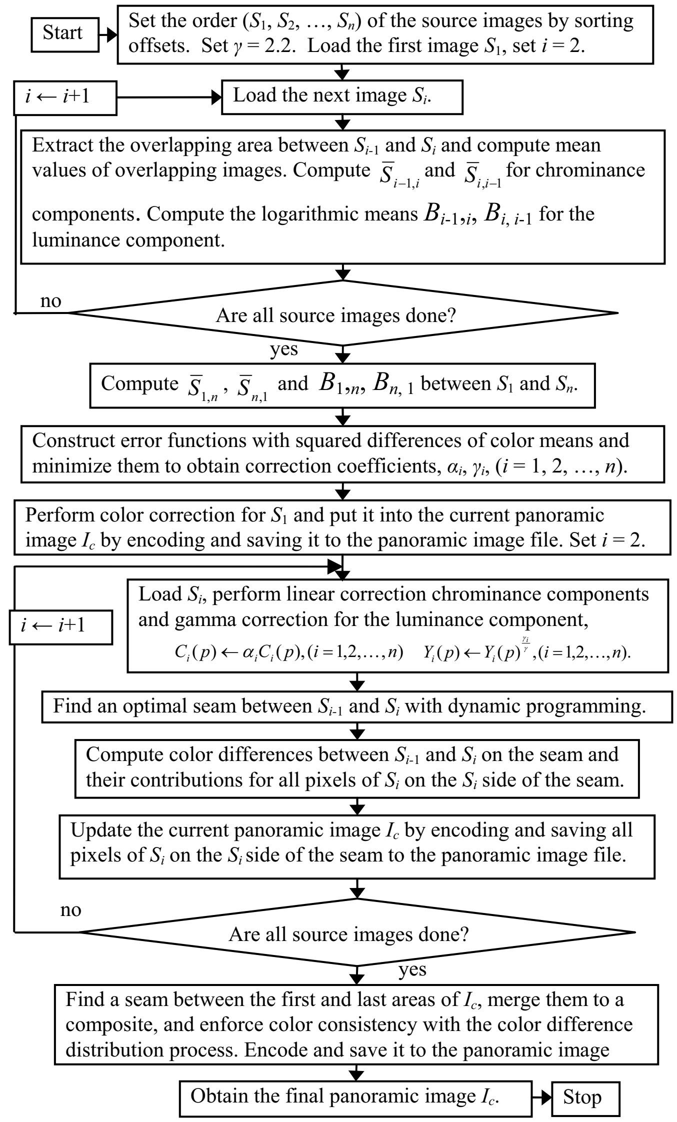

Fig. 1. Workflow of the panorama stitching with color matching.

III. Details of the Image Stitching Approach with Color Correction

A. Problem Expression

Since image parameters are automatically recalculated for each input image during panorama capture, changes in illumination levels lead to different exposure levels in adjacent images, and different distribution of variously colored objects affects the white-balance settings, yielding images where the same objects seen in different images appear different, either brighter or darker, or even have different apparent colors.

Fig. 2. Image stitching without color processing.

Fig. 3. Result of local linear color correction.

Fig. 4. Color differences between the first and last areas of a 360-degree panoramic image.

Fig. 2 shows an example. When stitching 9 images with different colors and luminance (bottom) without any color processing, we obtain the result (top) in which the seams and stitching artifacts can be clearly seen.

Color correction can reduce color differences between source images and smooth color transitions for the whole image sequence, improving the quality and speed of later operations such as optimal seam finding and image blending, hence improving the quality of final panoramic images [2], [16]. It is necessary to perform color correction for the source images before stitching them together.

Linear-model-based color correction is simple and fast. It does not need exact pixel correspondences. However, as described before, there are several problems in linear color correction: pixels are easily saturated during color correction, especially when the color correction errors accumulate as we process the image sequence, and the order of source images in the color correction process and the quality of the first image affect the final result. Fig. 3 shows an example result created by a linear color-correction approach [3]. From the result we can see that pixels in many areas such as the sky and the road are saturated and details in these areas are lost. Due to cumulative errors, the panoramic image becomes brighter from left to right. Since the first image remains unchanged, its bad colors twist the colors of the whole sequence. Since the color correction is performed locally, color transitions in the panoramic image are not good.

We want to create a color and luminance compensation approach that avoids pixel saturation problems, removes cumulative errors, makes the correction process independent of the correction order of the source images, and adjusts color and luminance globally over the whole image sequence. In order to do this, we perform color and luminance compensation for the source images based on the combination of gamma correction for luminance and linear correction for chrominance and use a global optimization process to obtain correction coefficients at once for the whole image sequence.

In creating a 360-degree panoramic image, there is an additional color consistency problem. Fig. 4 shows an example. In this case, there are 19 source images in the image sequence shown at the bottom. The colors and luminance in the source images are very different. Fig. 4 (top) shows a panoramic image created with the image sequence. The start and end of the panorama overlap, but have quite different colors, as highlighted by the red rectangles. Instead, the colors and luminance should be similar. In this example, they are different, which makes the panoramic image look unrealistic. Our stitching approach creates two processes, color correspondence and color difference distribution, to ensure color consistency of the 360-degree panoramic image.

B. Color Correction

1) Gamma and Linear Correction Coefficients

For an image sequence S_1, S_2, S_3, …, S_n, we match the luminance in the overlapping areas of the adjacent images with gamma correction and construct an error function,

$$\min E_1 = \frac{1}{2}\left(\sum_{i=2}^{n} (\gamma_{i-1} B_{i-1,i} - \gamma_i B_{i,i-1})^2 / \sigma_N^2 + \sum_{i=1}^{n} (1-\gamma_i)^2 / \sigma_g^2 \right), \quad (1)$$

where σ_N and σ_g are the standard deviations of the normalized color and luminance errors and gamma coefficients. We choose values $\sigma_N = 2.0/255$ and $\sigma_g = 0.5/255$ (when the image value range is normalized to [0, 1]),

$$B_{i-1,i} = \ln\left(\frac{1}{N_{i-1,i}} \sum_p Y_{i-1,i}(p) \right), B_{i,i-1} = \ln\left(\frac{1}{N_{i-1,i}} \sum_p Y_{i,i-1}(p) \right), \quad (2)$$

$Y_{i-1,i}(p)$ is the luminance value of pixel p in the image $S^o_{i-1,i}$ (linearized from the *sRGB* luminance by raising to the power of γ = 2.2); $Y_{i,i-1}(p)$ is the luminance value of the corresponding pixel p in image $S^o_{i,i-1}$; γ_{i-1} and γ_i are gamma-correction coefficients for images i-1 and i; $N_{i-1,i}$ is the number of pixels in the overlapping area.

By minimizing the error function E_1, we can obtain the gamma coefficients γ_i (i = 1, 2, …, n).

In a similar way, we can match the chrominance in the overlapping areas of the adjacent images with linear correction and construct an error function,

$$\min E_2 = \frac{1}{2}\left(\sum_{i=2}^{n} (\alpha_{i-1} \bar{S}_{i-1,i} - \alpha_i \bar{S}_{i,i-1})^2 / \sigma_N^2 + \sum_{i=1}^{n} (1-\alpha_i)^2 / \sigma_g^2 \right). \quad (3)$$

where $\bar{S}_{i-1,i}$ and $\bar{S}_{i,i-1}$ is the chrominance mean value of image $S^o_{i-1,i}$ and image $S^o_{i,i-1}$ respectively,

$$\bar{S}_{i-1,i} = \frac{1}{N_{i-1,i}} C_{i-1,i}(p), \bar{S}_{i,i-1} = \frac{1}{N_{i-1,i}} C_{i,i-1}(p), \quad (4)$$

$C_{i-1,i}(p)$, $C_{i,i-1}(p)$ are the chrominance values of pixel p in overlapping images $S^o_{i-1,i}$, $S^o_{i,i-1}$. α_i (i = 1, 2, …, n) are linear correction coefficients.

Solving this quadratic objective function, we can obtain the linear correction coefficients α_i (i = 1, 2, …, n).

2) Color and Luminance Correction

For each source image, we perform gamma correction for the luminance component,

$$Y_i(p) \leftarrow Y_i(p)^{\frac{\gamma_i}{\gamma}}, (i = 1,2,\ldots,n), \quad (5)$$

where γ is the gamma coefficient used above for linearization of the *sRGB* color space, and linear correction for the chrominance components,

$$C_i(p) \leftarrow \alpha_i C_i(p), (i = 1,2,\ldots,n). \quad (6)$$

3) Color Correspondence Process

We create a color correspondence process for 360-degree panorama construction. In this case, there is an overlapping area between the beginning and ending areas. We add the luminance and color information in these areas into the global color matching process. For luminance matching, the error function (1) becomes,

$$\min E_3 = \frac{1}{2}(\gamma_1 B_{1,n} - \gamma_n B_{n,1})^2 / \sigma_N^2 + \frac{1}{2}\sum_{i=2}^{n} (\gamma_{i-1} B_{i-1,i} - \gamma_i B_{i,i-1})^2 / \sigma_N^2 + \frac{1}{2}\sum_{i=1}^{n} (1-\gamma_i)^2 / \sigma_g^2 . \quad (7)$$

The first item $\frac{1}{2}(\gamma_1 B_{1,n} - \gamma_n B_{n,1})^2/\sigma_N^2$ in error function (7) matches luminance between the first and last images in the image sequence. Solving this function, we obtain new gamma correction coefficients.

In the same way, we can add chrominance matching between the first and last images to (3) to create a new error function for new linear correction coefficients.

The luminance and color matching yields color consistency for the beginning and ending areas of the 360-degree panoramic image.

C. Image Labeling

We use the labeling approach described by Xiong and Pulli [12] to find optimal seams in the overlapping areas between source images and merge them into a panoramic image.

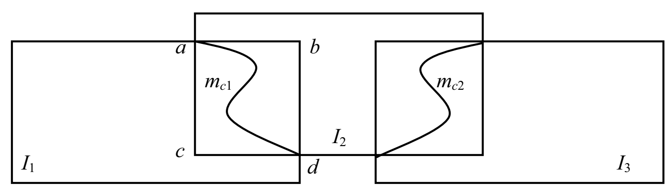

Fig. 5. Optimal seam finding for image labeling.

Fig. 5 shows the labeling process. In this approach, the optimal seam finding process is performed by dynamic programming. After extracting the overlapping area *abcd*, shown in Fig. 5, between image I_1 and image I_2, we construct an error surface with squared differences of colors in the overlapping area. We scan the error surface row by row and compute a cumulative minimum squared difference. An optimal path m_{c1} can be found by dynamic programming with the cumulative minimum squared difference. We use the optimal path as an optimal seam to merge the source images together. In our sequential panorama stitching approach, the source images are merged to the panoramic image one by one sequentially to save memory.

For 360-degree panorama construction, we additionally need to find an optimal seam between the begin and end areas of the panoramic image and merge them along the seam to create a continuous circular 360-degree panoramic image.

D. Image Blending

1) Color Blending

Through color matching, color differences of source images in the whole image sequence can be reduced. Color transitions in the whole panoramic image can be smoothed.

However, the color matching only provides an approximate match, leaving still visible color differences. Image blending can further reduce the color differences and provide smooth color transitions for the panoramic image. We use an effective blending approach with fast processing speed and high blending quality explained below.

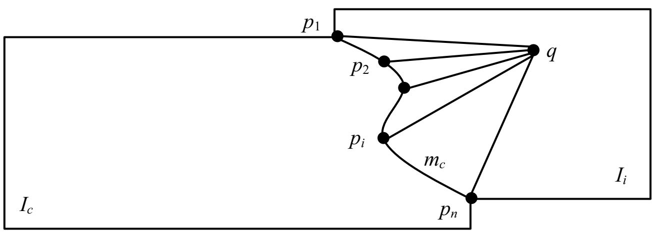

Fig. 6. Mean value coordinates based image blending.

As shown in Fig. 6, let $p_1, p_2, \ldots, p_n$ be the n points on the seam m_c, $D_1, D_2, \ldots, D_n$ be the color differences at those points between the overlapping images, and q be a pixel of the blending image. We then interpolate the color differences at pixel q by

$$D(q) = \sum_{i=1}^{n} w_i(q) D(p_i), \tag{9}$$

where the weights are the inverse coordinate distances to the boundary pixels, normalized so that they sum up to 1:

$$w_i(q) = \frac{1/\| p_i - q \|}{\sum_{j=1}^{n} 1/\| p_j - q \|}. \tag{10}$$

We add these changes to the pixels in the blending area.

$$C(q) \leftarrow C(q) + D(q), \tag{11}$$

where $C(q)$ is the color value at pixel q.

2) Color Difference Distribution Process

In the sequential image stitching process, the source images are stitched to the panoramic image one by one sequentially. The colors of the current stitching image are affected by the previous image to keep color transitions smooth. In practice, this means that the colors at the end of the panorama are quite unlikely to match the colors in the beginning of the panorama. However, in case of a 360-degree panorama, we want no discontinuity in the colors as the panorama wraps around. We create a color difference distribution process to enforce color consistency when the panorama is connected from the end back to the beginning.

Fig. 7 shows the color distribution process for a 360-degree panoramic image. I_b and I_e are two overlapping image patches extracted from the beginning and ending areas of the panoramic image, respectively. We find an optimal seam m_s with the approach described in Section III.D, and merge them together along the seam to create a composite image. In order to make colors consistent in these two images, we keep image I_e on the left side of the seam unchanged and distribute color differences on the seam to image I_b on the right side of the seam. Since image I_b is extracted from the beginning of the panoramic image, we need to keep the color unchanged at the end of image I_b, so that we can keep color consistency between image I_b and the original part of the panoramic image. Here is the color difference distribution process.

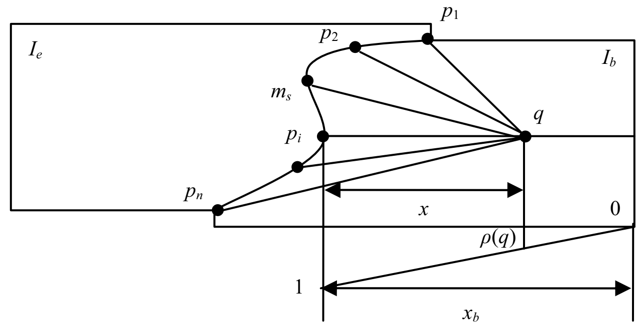

Fig. 7. Color difference distribution for 360-degree panoramic images

We blend the images to distribute the color differences to the blending area and gradually attenuate the color changes with respect to the distance to the seam until the changes are zero at the end of I_b. We attenuate the color of the pixel q in the blending area on the current scan line with

$$C(q) \leftarrow C(q) + \rho(q) D(q), \tag{12}$$

where, $D(q)$ is calculated with Equation (9); $\rho(p) \in \{0,1\}$ is a ratio which changes linearly from 1 on the seam to 0 at the end of the blending area,

$$\rho(p) = 1 - \frac{x}{x_b}; \tag{13}$$

x is the horizontal distance between pixel q and the seam on the current scan line; and x_b is the horizontal distance between the seam and the end of the blending area.

After all pixels in the blending area are updated, we put the composite image back to the original panoramic image to create a continuous circular 360-degree panoramic image.

In order to store the panoramic image in a 2D array and display it easily, we cut the continuous circular panoramic image along a vertical line.

Fig. 8 (top) and (middle) show the results created by the image stitching approach with color matching for the same source images shown in Fig. 2 and Fig. 3, respectively. From the results we can see that color differences between source images are reduced, stitching artifacts are removed, and color transitions in the panoramic images are smoothed. All linear correction problems are avoided. Fig. 8 (bottom) shows the result created by the image stitching approach with the color correspondence and color difference distribution processes for the same source images as shown in Fig. 4. The quality of the panoramic image is much higher than the previous one. It has much better color consistency in the beginning and ending areas and better transitions in the whole panoramic image.

Fig. 8. Panoramic images created by image stitching with color matching.

IV. APPLICATIONS AND RESULT ANALYSIS

The panorama stitching approach has been implemented in a mobile panoramic imaging system and run on camera phones to create high-quality and high-resolution panoramic images. It has been tested with different image sequences and produces good results with source images that have very different colors and luminance. The results in this section were obtained on a mobile phone with a 600 MHz processor, 256 MB RAM, 768 MB virtual memory, and a 3.5 inch touch-sensitive widescreen display. It can also be run on other, less capable mobile devices. The results are satisfying.

A. Performance Measurements

We evaluated the computation time of the stitching approach on the mobile phone described above using image sequences with source images of different resolutions including 1280×960, 2048×1536, and 2576×1936. There are two image sequences with 5 and 10 images for each resolution.

TABLE I
PERFORMANCE EVALUATION OF THE STITCHING APPROACH

Resolution	Time for 5 Images (sec.)				Time for 10 Images (sec.)			
	A	B	C	D	A	B	C	D
1280×960	0.37	3.30	2.48	6.15	0.97	6.96	5.44	13.37
2048×1536	1.08	6.72	4.70	12.50	1.56	14.44	10.46	26.46
2576×1936	1.86	15.98	12.25	30.09	4.12	35.63	29.34	69.09

TABLE I shows the computational time for each test case, where A, B, C, D are the times for color correction, image labeling, image blending, and complete image stitching which adds A B C together. For example, in the case of 1280×960 10 source images, the full stitching time is 13.37 seconds. Among them the color correction, labeling, and blending take 0.97 seconds, 6.96 seconds, and 5.44 seconds respectively.

B. Color Correction and Comparison with Other Approaches

Fig. 9 shows a comparison of panoramic images created by different color and luminance correction approaches. In this application, there are 17 source images in the image sequence shown in Fig. 9 (e). From the image sequence we can see that the colors and luminance of the source images are very different. When the source images are stitched together without any color and luminance processing, the differences of colors and luminance in the composite image can still be visible. Color correction and transition smoothing are needed to reduce these differences.

Fig. 9 (a) shows a panoramic image created by image stitching with the local linear color correction described in [3]. From the result we can see the problem of pixel overflow in several areas such as the sky near the tower, the road near the light pole, and so on. The whole image is too bright after color correction and many details have disappeared. Color transitions are not good, especially at the left and the right hand sides of the image.

Fig. 9 (b) shows a panoramic image created by image stitching with the color correction described in [4] which uses linear models in the *YCbCr* color space. There are similar problems as the result shown in Fig. 9 (a). Pixels in many areas are saturated, most details are lost, color transitions in the whole image are not good, and the order of the source images in color correction process affects the final result.

Fig. 9 (c) shows a result created by image stitching with the global linear color correction described in [5] in which the approach is used for luminance correction only. Here we use it for color correction in the *sRGB* color space. From the result we can see that there are no color overflow problems after color correction. However, the quality of the panoramic image is still not good. Some source images are corrected too much,

Fig. 9. Comparison of results created by different color correction approaches. From top to bottom, (a) Local linear correction in [3], (b) Color correction by the approach in [4], (c) Global linear correction [5], (d) Gamma correction using color matching, (e) Source images.

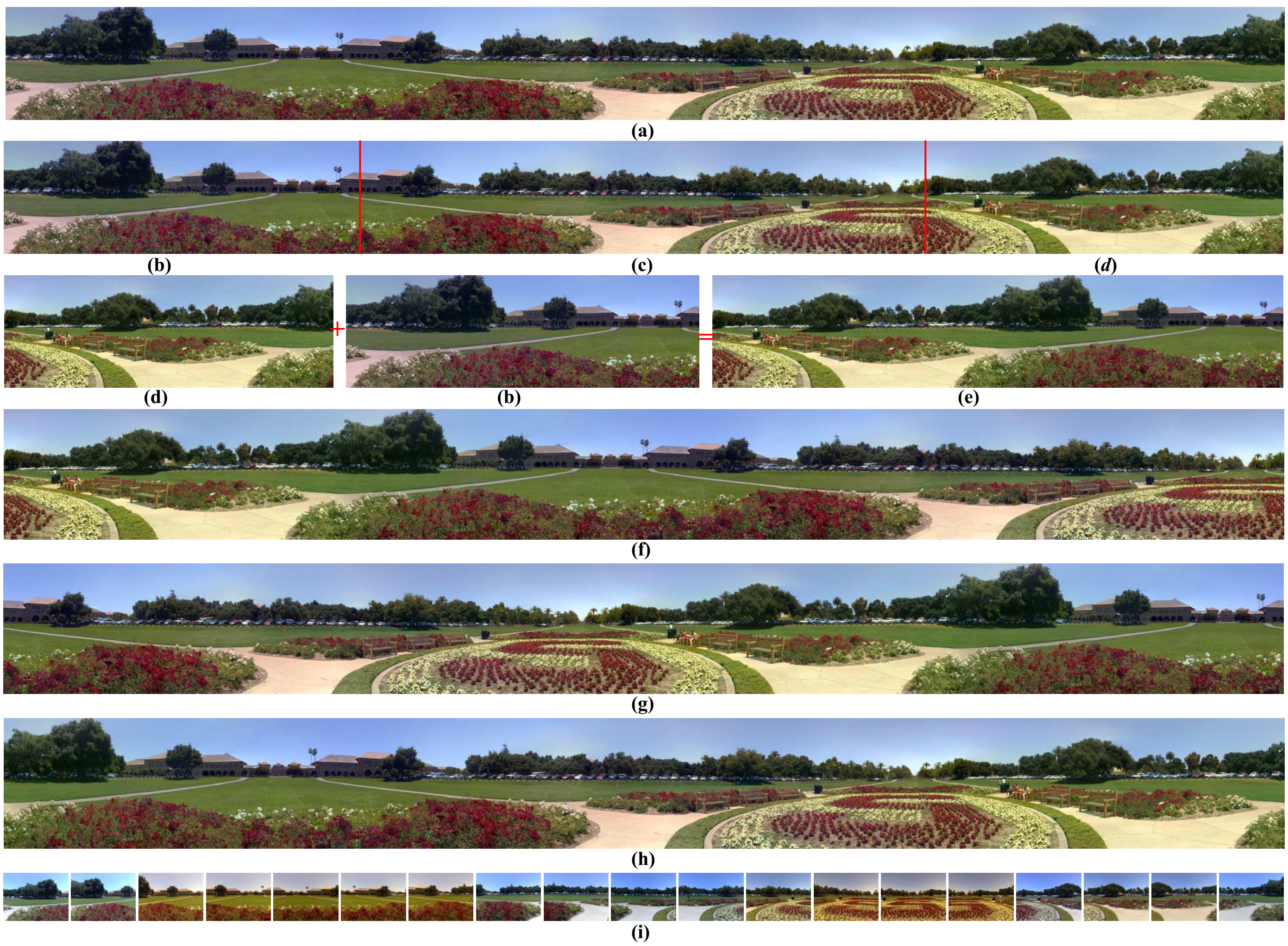

Fig. 10. Construction and color consistency of 360-degree panoramic images.

so that the images become too dark, such as on the far left and right sides of the image. The reason is that the source images at the beginning and the end of the image sequence are too bright. For the balance of colors and luminance of the whole panoramic image, the approach performs a too severe correction for these source images.

Fig. 9 (d) shows a panoramic image created by image stitching using gamma-corrected color mean matching. We perform gamma-correction for the luminance component and linear correction for chrominance components in the *YCbCr* color space. From the panoramic image we can see that it is the best result among these cases. All the problems mentioned

Fig. 11. More 360-degree panoramic images obtained by the panorama stitching approach.

above are solved. There is no color overflow; the corrections are not too severe. The color balance and color transitions are very good in the whole panoramic image. All details of the source images are retained in the result. There are no too dark and bright areas caused by color correction.

Construction of 360-degree Panoramic Images

Fig. 10 shows an application of creating continuous circular 360-degree panoramic images with different processes for an image sequence captured in an outdoor scene. There are 19 source images in the image sequence with very different colors and luminance. Some images are saturated and others have unrealistic colors. The image sequence is shown in Fig. 10 (i), which is a good image sequence for testing color correction and image stitching approaches.

Fig. 10 (a) shows the panoramic image created by the panorama stitching process including color correction, image labeling, and image blending without color consistency processing. From the result we can see that the panorama stitching approach is very effective and it can be used for creating high-resolution and high-quality panoramic images from long image sequences with very different colors and luminance. During panorama construction, the differences of colors and luminance in source images are reduced; the unrealistic colors of the source images are corrected; and color transitions in the whole panoramic image are smoothed.

This is a 360-degree panorama. There is an overlapping area in the beginning and the ending areas of the panoramic image. From the result shown in Fig. 10 (a) we can see that the colors and luminance are different in these areas that cover the same scene, but they should be consistent. This is one of the main problems that we address in this paper. The color correspondence and color difference distribution processes described in Section III.B and Section III.D can be used to solve this problem.

In 360-degree panorama color consistency processing, we extract an image patch I_b from the beginning and another image patch I_d from the end of the panoramic image. They are shown in Fig. 10 (b) and (d) which overlap each other. The rest of the panoramic image I_c is shown in Fig. 10 (c). With the 360-degree panorama labeling described in Section III.C, we can find an optimal seam between these two image patches and merge them together into a composite image I_e. In order to remove stitching artifacts caused by the color differences between these two areas and make color consistency between the composite image I_e and image I_c, we blend the color differences on the seam to the blending area with the color difference distribution process. The result of the blended composite image I_e processed by 360-degree panorama color consistency method is shown in Fig. 10 (e). From the result we can see that the seam between these two image patches is invisible; color differences are removed; color changes are gradually reduced from left to right; and there is no color change at the end of the composite image I_e, so that it can match the beginning of image I_c.

Fig. 10 (f) shows the result which we put the composite image I_e to the beginning of the rest of the panoramic image I_c to create an exact 360-degree panoramic image I_f. From the result we can see that the composite image I_e and the rest of the panoramic image I_c match perfectly without any visible artifact, which also proves that the 360-degree panorama color consistency process is very effective. The result also shows that the beginning and ending of the panoramic image I_f match exactly without any artifact, since the previous is simply cut from the latter. By comparing with the original panoramic image Fig. 10 (*a*), the created 360-degree panoramic image I_f has much better color consistency between the beginning and ending areas and the color transitions are smooth across the whole panoramic image.

Fig. 10 (g) shows the results where we put the composite image I_e to the end of the panoramic image I_c, and Fig. 10 (h) where half of the composite image I_e goes to the beginning and another half to the end of the panoramic image I_c.

Fig. 11 shows additional 360-degree panoramic images created by the stitching approach with color matching. Fig. 11 (top) shows a result for another outdoor scene and Fig. 11 (bottom) shows a result for an indoor scene. From the results we can see that the panorama stitching approach can be used for creating high-quality 360-degree panoramic images with good color consistency in the beginning and ending areas and good color transitions for both indoor and outdoor scenes.

V. Discussion and Conclusions

We presented an image stitching approach which can be used for creating high-resolution and high-quality continuous circular 360-degree panoramic images with good color consistency and color transitions. The approach includes color correction, image labeling, and image blending.

We use gamma-correction to reduce color differences between source images and balance colors and luminance in the whole image sequence. The gamma coefficients are obtained by color matching in the overlapping areas of the source images. One of the main advantages of gamma color correction is that pixel saturation problems during the color correction process can be avoided. An optimal seam finding process finds optimal seams in the overlapping areas of the source images, helping to merge them together into a panoramic image. The optimal seam finding process is performed by dynamic programming with fast speed and low memory consumption. An image blending process is used to further reduce color differences between source images and to smoothen color transitions for the whole panoramic image. In the blending process, we distribute color differences on the seams to the pixels in the blending areas to obtain high-quality blended images with fast speed and low memory consumption.

We have addressed the color consistency problem between the beginning and ending areas of the 360-degree panoramic image. During image capture, different view angles of the camera and changes of scene illumination may lead to different colors and luminance in neighboring images. Especially when processing long image sequences for 360-degree panoramic images, the colors and luminance between the first and last images end up to be very different. If no further color processing is done, the panoramic image has a color discontinuity. We developed two processes, color correspondence and color difference distribution, to deal with the problem. In the color correspondence process, we add the information of color matching in the beginning and ending areas of the panoramic image to the color correction process to balance colors in the whole image sequence. In the color difference distribution process, we find an optimal seam between the beginning and ending areas, merge them together along the seam to create a continuous circular panoramic image, and distribute the color differences from the seam to the blending area to guarantee color consistency.

We have implemented the approach in a panoramic imaging system and run on mobile phones to create high-resolution and high-quality panoramic images. Some example applications and results are given in this paper. From the results we can see that the stitching approach can create high-quality 360-degree panoramic images with good color consistency and good color transitions. The approach has been tested with many image sequences captured in different scenes producing good results and performance.

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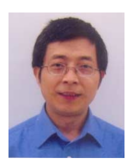
BIOGRAPHIES



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